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PROBLEMS OF THE OPTIMAL CONSTRUCTION OF FERRITE PHASE SHIFTERS --ETC(U)

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by

A. K. Stolyarov, I. A. Naumov

FOREIGN TECHNOLOGY DIVISION

EDITED TRANSLATION

14 FTD-ID(RS)T-0642-81 1 22 Jul[redacted]81

MICROFICHE NR: FTD-81-C-000709

6 PROBLEMS OF THE OPTIMAL CONSTRUCTION OF FERRITE PHASE SHIFTERS WITH RECTANGULAR HYSTERESIS LOOP

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~~English pages: 8~~

21 Edited trans. of

~~Source:~~ Antenny ~~Nr. 8, 1970, pp. 65-72~~

(USSR) n8 p65-72 1970, by

Country of origin: USSR

Translated by: Robert D. Hill.

Requester: FTD/TQFE

Approved for public release; distribution unlimited.

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П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.

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Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	$\sinh^{-1}$
cos	cos	ch	cosh	arc ch	$\cosh^{-1}$
tg	tan	th	tanh	arc th	$\tanh^{-1}$
ctg	cot	cth	coth	arc cth	$\coth^{-1}$
sec	sec	sch	sech	arc sch	sech^{-1}
cosec	csc	csch	csch	arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

PROBLEMS OF THE OPTIMAL CONSTRUCTION OF FERRITE PHASE SHIFTERS WITH RECTANGULAR HYSTERESIS LOOP

A.K. Stolyarov, I.A. Naumov

The article gives results of the calculation of a unidirectional waveguide phase shifter, which is presented in the form of ferrite dielectric waveguide magnetized by a ring magnetic field, the ferrite having an arbitrary thickness. The problem of the propagation of the electromagnetic wave along a two-layer dielectric rod is strictly solved, and the unidirectional effect is found by the perturbation method.

A calculation of the waveguide phase shifters with ferrite having a rectangular hysteris loop (PPG) was carried out in work [1]. The phase shifter was presented in the form of a dielectric waveguide covered by a thin layer of ferrite.

For practical purposes it is important to examine the more complex system in which the ferrite can have an arbitrary thickness. Examined for this purpose is the propagation of a wave along the two-layer dielectric waveguide (Fig. 1), and then calculated by the perturbation method is the unidirectional phase shift under the assumption that the external dielectric cylinder (region II) possesses gyromagnetic properties.

The selected method allowed avoiding complex expressions in the form of series for the constant propagation and quite simply analyzing the effect on the magnitude of the phase shift of dimensions and parameters of the dielectric and ferrite cylinders.

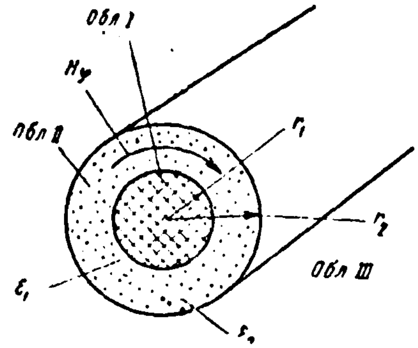

Fig. 1. Key: 1) Region I; 2) Region II; 3) Region III.

For waves of the HE_{1n} type, the initial fields are recorded in the form:

region III $(r \geqslant r_2)$

$$\left.\begin{aligned} E^0_{z_3} &= -p^2 C_1 K_1(pr)\sin\varphi \\ E^0_{r_3} &= i\left[\gamma_0 C_1 p K_1'(pr) - \frac{\kappa_0}{r} C_2 K_1(pr)\right]\sin\varphi \\ E^0_{\varphi_3} &= i\left[\frac{\gamma_0}{r} C_1 K_1(pr) - \kappa_0 p C_2 K_1'(pr)\right]\cos\varphi \end{aligned}\right|; \qquad (1a)$$

$$\left.\begin{aligned} H^0_{z_3} &= -p^2 C_2 K_1(pr)\cos\varphi \\ H^0_{r_3} &= i\left[\gamma_0 p C_2 K_1(pr) - \frac{\kappa_0}{r} C_1 K_1(pr)\right]\cos\varphi \\ H^0_{\varphi_3} &= i\left[\kappa_0 p C_1 K_1'(pr) - \frac{\gamma_0}{r} C_2 K_1(pr)\right]\sin\varphi \end{aligned}\right|, \qquad (1b)$$

where γ_0 is the constant of propagation;

$K_1'(pr)$ - the McDonald function and its derivative; $\kappa_0 = \frac{\omega}{c}$; $p^2 = \gamma_0^2 - \kappa_0^2$; $K_1(pr)$.

region II $(r_1 \leqslant r \leqslant r_2)$

$$\left.\begin{aligned} E^0_{z_2} &= g_2^2 [B_1 J_1(g_2 r) + B_2 N_1(g_2 r)]\sin\varphi \\ E^0_{r_2} &= i\Big\{\gamma_0^2 g_2 [B_1 J_1'(g_2 r) + B_2 N_1'(g_2 r)] - \frac{\kappa_0}{r}[B_3 J_1(g_2 r) + \\ &\quad + B_4 N_1(g_2 r)]\Big\}\sin\varphi \\ E^0_{\varphi_2} &= i\Big\{\frac{\gamma_0}{r}[B_1 J_1(g_2 r) + B_2 N_1(g_2 r)] - \kappa_0 g_2 [B_3 J_1'(g_2 r) + \\ &\quad + B_4 N_1'(g_2 r)]\Big\}\cos\varphi \end{aligned}\right|; \qquad (2a)$$

$$
\left.\begin{aligned}
H^0_{z_2} &= g_2^2 [B_3 J_1(g_2 r) + B_4 N_1(g_2 r)] \cos\varphi \\
H^0_{r_2} &= \mathrm{i}\left\{\gamma_0 g_2 [B_3 J_1'(g_2 r) + B_4 N_1'(g_2 r)] - \frac{\kappa_0}{r}\varepsilon_2 [B_1 J_1(g_2 r) + \right. \\
&\quad \left. + B_2 N_1(g_2 r)]\right\} \cos\varphi \\
H^0_{\varphi_2} &= \mathrm{i}\left\{\kappa_0 \varepsilon_2 g_2 [B_1 J_1'(g_2 r) + B_2 N_1'(g_2 r)] - \frac{\gamma_0}{r} [B_3 J_1(g_2 r) + \right. \\
&\quad \left. + B_4 N_1(g_2 r)]\right\} \sin\varphi
\end{aligned}\right\}, \qquad (2b)
$$

where $g_2^2 = \kappa_2^2 - \gamma_0^2$; $\kappa_2^2 = \kappa_0^2 \varepsilon_2$; $J_1(gr)$, $J_1'(gr)$, $N_1(gr)$, $N_1'(gr)$ are Bessel functions of the first and second kind and their derivatives;

region I ($r \leqslant r_1$)

$$
\left.\begin{aligned}
E^0_{z_1} &= g_1^2 A_1 J_1(g_1 r) \sin\varphi \\
E^0_{\varphi_1} &= \mathrm{i}\left[\frac{\gamma_0}{r} A_1 J_1(g_1 r) - \kappa_0 g_1 A_2 J_1'(g_1 r)\right] \cos\varphi \\
E^0_{r_1} &= \mathrm{i}\left[\gamma_0 g_1 A_1 J_1'(g_1 r) - \frac{\kappa_0}{r} A_2 J_1(g_1 r)\right] \sin\varphi
\end{aligned}\right\}; \qquad (3a)
$$

$$
\left.\begin{aligned}
H^0_{z_1} &= g_1^2 A_2 J_1(g_1 r) \cos\varphi \\
H^0_{\varphi_1} &= \mathrm{i}\left[\kappa_0 \varepsilon_1 g_1 A_1 J_1'(g_1 r) - \frac{\gamma_0}{r} A_2 J_1(g_1 r)\right] \sin\varphi \\
H^0_{r_1} &= \mathrm{i}\left[\gamma_0 g_1 A_2 J_1'(g_1 r) - \frac{\kappa_0}{r} \varepsilon_1 A_1 J_1(g_1 r)\right] \cos\varphi
\end{aligned}\right\}. \qquad (3b)
$$

From boundary conditions when $r=r_1$ and $r=r_2$, we obtain eight homogeneous equations, from which the relative values of coefficients A, B and C and the propagation constant γ_0 can be determined. The determinant of the indicated system of equations has the form:

$$
\begin{vmatrix}
\mathrm{i}\frac{\eta}{r_1} & \mathrm{i}\kappa_0 g_1 \alpha & -\mathrm{i}\frac{\eta}{r_1}\beta & -\mathrm{i}\frac{\eta}{r_1}\gamma. & \mathrm{i}\kappa_0 g_2 \xi & \mathrm{i}\kappa_0 g_2 \gamma_l & 0 & 0 \\
g_1^2 & 0 & -g_2^2\beta & -g_2^2\gamma. & 0 & 0 & 0 & 0 \\
\mathrm{i}\kappa_0 g_1 \varepsilon_1 \alpha & -\mathrm{i}\frac{\eta}{r_1} & -\mathrm{i}\kappa_0 \varepsilon_2 g_2 \xi & -\mathrm{i}\kappa_0 \varepsilon_2 g_2 \gamma_l & \mathrm{i}\frac{\eta}{r_1}\beta & \mathrm{i}\frac{\eta}{r_1}\gamma. & 0 & 0 \\
0 & g_1^2 & 0 & 0 & -g_2^2\beta & -g_2^2\gamma. & 0 & 0 \\
0 & 0 & \mathrm{i}\frac{\eta}{r_2} & \mathrm{i}\frac{\eta}{r_2}\Theta & \mathrm{i}\kappa_0 g_2 \Delta & -\mathrm{i}\kappa_0 g_2 \nu & -\mathrm{i}\frac{\eta}{r_2}\rho & \mathrm{i}\kappa_0 \rho\varkappa \\
0 & 0 & g_2^2 & g_2^2\Theta & 0 & 0 & p^2\rho & 0 \\
0 & 0 & \mathrm{i}\kappa_0 \varepsilon_2 g_2 \Delta & \mathrm{i}\kappa_0 \varepsilon_2 g_2 \Theta & -\mathrm{i}\frac{\eta}{r_2} & -\mathrm{i}\frac{\eta}{r_2}\Theta & \mathrm{i}\kappa_0 \rho\varkappa & \mathrm{i}\frac{\eta}{r_2}\rho \\
0 & 0 & 0 & 0 & g_2^2 & g_2^2\Theta & 0 & p^2\rho
\end{vmatrix} = 0.
$$

where

$$\alpha = \frac{J_1'(g_1 r_1)}{J_1(g_1 r_1)}; \quad \beta = \frac{J_1(g_2 r_1)}{J_1(g_1 r_1)}; \quad \gamma = \frac{N_1(g_2 r_1)}{J_1(g_1 r_1)};$$

$$\gamma_1 = \frac{N_1'(g_2 r_1)}{J_1(g_1 r_1)}; \quad \xi = \frac{J_1'(g_2 r_1)}{J_1(g_1 r_1)}; \quad \Theta = \frac{N_1(g_2 r_2)}{J_1(g_2 r_2)}; \quad \Lambda = \frac{J_1'(g_2 r_2)}{J_1(g_2 r_2)};$$

$$\rho = \frac{K_1(p r_2)}{J_1(g_2 r_2)}; \quad \nu = \frac{N_1'(g_2 r_2)}{J_1(g_2 r_2)}; \quad \chi = \frac{K_1'(p r_2)}{J_1(g_2 r_2)}.$$

The tensor of the magnetic permeability of the ferrite is given in [2].

The magnitude of the nonreciprocal increase in $\Delta\gamma$ of the propagation constant is determined by the perturbation method:

$$\Delta\gamma = \frac{k \int\limits_{S_2} \left(H_r H_z^{0*} - H_z H_r^{0*}\right) dS}{\frac{2}{\kappa_0} \int\limits_{S} \left[E_r^0 H_\varphi^{0*} - E_\varphi^0 H_r^{0*} \right] dS}, \qquad (5)$$

where S is the total area of the cross section through which the electromagnetic wave passes;

S_2 - the area of cross section of the ferrite.

Having substituted into equation (5) expressions for fields from (1), (2) and (3), and assuming for ferrites with PPG that $\mu=1$, we obtain the final formula for $\Delta\gamma$.

Part of the integrals entering into the final formula for $\Delta\gamma$ are tabular, and the remaining ones are computed according to the Simpson method.

Let us examine the case when the dielectric constants of the ferrite and dielectric are considerably different. Let us assume that $\varepsilon_1 \gg \varepsilon_2$; then at a definite value of r_1 the wave propagation constant γ_0 will be greater than $K_0\sqrt{\varepsilon_2}$, and the transverse wave number g_2 will become imaginary. In this case functions $J_1(g_2 r)$ and $N_1(g_2 r)$ should be replaced in all formulas by functions $I_1(g_2 r)$ and $K_1(g_2 r)$, and in the determinant (4) they should be changed to the opposite signs near terms containing the factor g_2^2. A similar change in the formulas in the calculation process should be made in those cases when $\varepsilon_2 \gg \varepsilon_1$, and the transverse wave number g_1 becomes imaginary.

Let us examine the effect of the thickness of the ferrite on the quantity $\Delta\gamma$. First of all, let us discuss the simplest case when the dielectric constant of the ferrite and the dielectric are identical ($\varepsilon_1 = \varepsilon_2$). The corresponding calculation curves are given on Fig. 2. From them it is clear that the maximal nonreciprocal effect is reached when r_1=0, i.e., in a solid ferrite cylinder. The replacement of part of the ferrite by the dielectric [r_1=0.03; 0.05; 0.1 λ_0] changes the nature of the relation $\Delta\gamma = f(r_2)$; however, the absolute magnitude of the unidirectional [nonreciprocal] phase shift is decreased with an increase in r_1. Therefore, the use of the dielectric with the same permeability as the ferrite can be useful only for control of the shape of the frequency characteristic of the phase shifter.

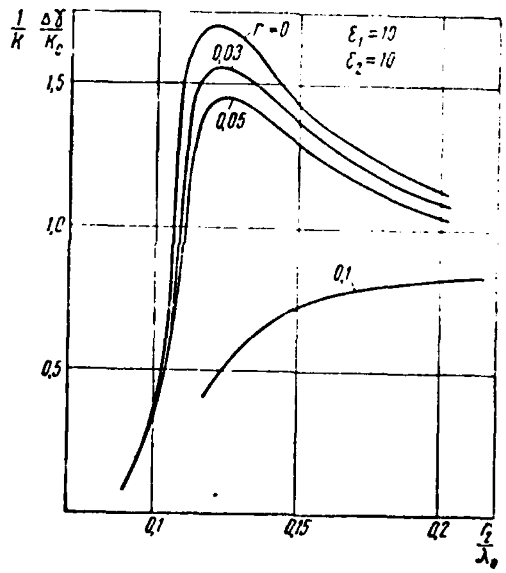

Fig. 2.

A comparison of curve r_1=0 on Fig. 2 with results of the precise calculation [4] shows that the maximal unidirectional phase shift takes place in both cases at practically identical diameters (an error of not more than 10%) of the ferrite cylinder; although, from the viewpoint of the approximation theory this case is most unprofitable, since the entire volume of the dielectric undergoes a disturbance. This confirms the expediency for using the perturbation method for solving similar problems.

Let us now examine the effect of the dielectric on the operation of the phase shifter for which a discussion of curves 3, 4 and 5 is given. At small values of r_1 (r_1=0.01 λ_0) the value of $\Delta\gamma$ is close to that value which corresponds to the solid ferrite cylinder (Fig. 2). With an increase in the diameter of the central dielectric (r_1=0.03; 0.04 λ_0, etc.), the magnitude of the differential phase shift is increased and at a certain r_1 reaches the maximal value. Consequently, for each value there are such dimensions of the dielectric and ferrite at which the greatest activity of the phase shifters is reached. Figure 5 gives the generalized curves according to which the maximally possible magnitude of the phase shift ($\Delta\gamma_{макс}$) for dielectrics with different ε can be determined. Just as in the case of a thin ferrite [1], $\Delta\gamma$ increases with an increase in ε of the dielectric.

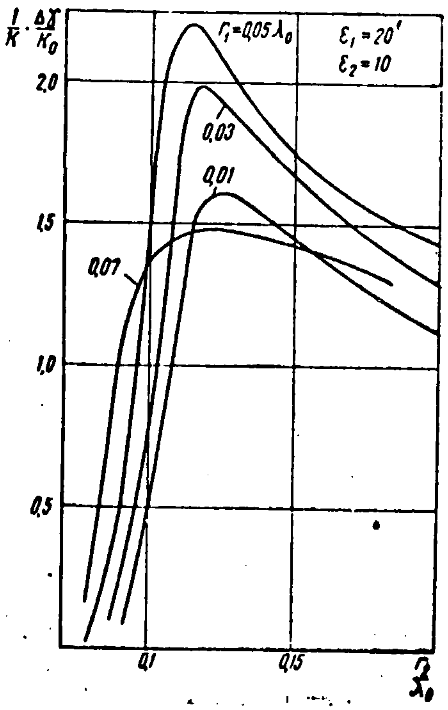

Fig. 3.

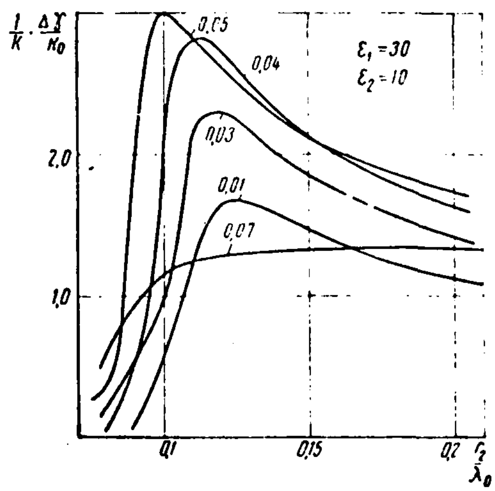

Fig. 4.

An important difference consists in the fact that the unidirectional phase shift reaches a maximum value at the smaller diameter of the ferrite. Thus when ε_1=10, $\Delta\gamma$ reaches a maximum at a diameter of the ferrite of d_2=0.4 λ_0, and in a thin ferrite tube the

maximum is observed when $d_2=0.24\,\lambda_0$. This denotes that by using the ferrite cylinders of optimal diameter, it is possible to lower considerably the magnitude of the control current. The use of a dielectric with high ε makes it possible to reduce significantly the length of the phase shifter and, consequently, decrease the energy of commutation, the magnitude of which is proportional to the volume of the ferrite. Let us note that owing to an increase in ε of the dielectric, it is not possible to lower the control current substantially, since the optimal diameter of the ferrite (Fig. 6) is insignificantly decreased with an increase in ε of the dielectric.

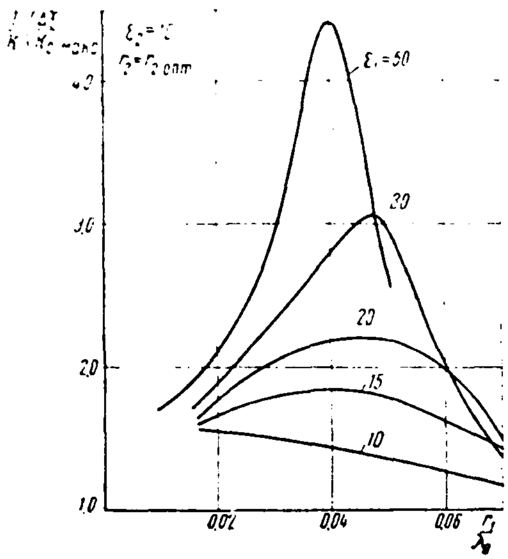

Fig. 5.

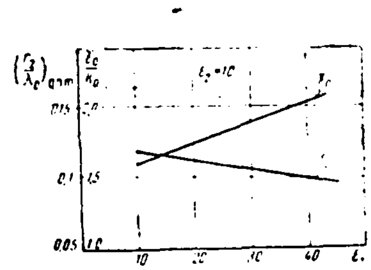

Fig. 6.

The curve which determines the wave propagation constant along the dielectric waveguide is plotted on Fig. 6. It indirectly characterizes the correctness of the selected model. As we see, the slowing down of the wave in the optimally fulfilled designs is significant, and, therefore, the metallic walls of the waveguide introduce insignificant corrections into the obtained results.

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